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CELSS SYSTEM CONTROL: ISSUES, METHODS, AND DIRECTIONS

C. C. Blackwell* and A. L. Blackwell**

*The Center for Dynamic Systems Control Studies, Department of Mechanical Engineering, The University of Texas at Arlington, Arlington, TX U.S.A., and M/S 239-4, NASA Ames Research Center, Moffett Field, California 94035 U.S.A.[1] **M/S 244-19, NASA Ames Research Center, Moffett Field, California 94035 U.S.A.

ABSTRACT

In the general control perspective, the CELSS concept implies a very complex system and presents challenges at every level. These challenges are generated by: (1) the prospect that the system will be inherently unstable, (2) the prospective difficulty of establishing an adequate mathematical model of the system for the purpose of control law synthesis (dimensionality is high, and the dynamics and interactive processes of some of the subsystems are not understood well), (3) assuring control law robustness (assuring that the resulting control law(s) will be effective over the domain of the specified uncertainties), (4) hardware realization of the control law, (5) hardware system robustness ("fault tolerance") and (6) achieving the logistics of the automation (or "management") aspects of the problem. A suggested organization of the problem, a sketch of the issues related to perceived difficulties, a commentary/evaluation of the issues, a review of methods available to address the issues, and a suggested strategy to address the broad CELSS systems control problem are presented.

INTRODUCTION

The effective realization of the CELSS requires that the actions taken to meet these challenges be carefully planned and coordinated, and that the most recently developed capabilities be included in the systems synthesis and design and in dealing with the issues which must be resolved.

Implicit in the CELSS concept is the need to develop a reliable bioregenerative system to provide life support for humans in space. The development of such a life support system can be aided through the use of mathematical modeling, analysis, control synthesis and simulation, each of which plays a valuable role throughout the development process: from the formulation of the conceptual design and the initial research on component processes through real time integration of the system with the crew.

THE GENERAL PROCESS OF CONTROL SYSTEM GENERATION

To help put the elements of the discussion to follow in relative and absolute perspective, the phases of the general control system realization process are next discussed. In brief: (1) Two mathematical models of the system to be controlled are generated: one to be used for control system synthesis and one for controlled system performance demonstration. (2) Based on the control system synthesis model, a control system preliminary design is made. It is tested via analysis and via simulation of the performance demonstration model for known particularly critical scenarios. (3) Preliminary hardware selection is made based on the preliminary design. Laboratory determination of component performance is done when needed. (4) The physical properties of the selected hardware are included in both models and the control system is reevaluated and refined based on these results. Experimental performance determination of subsystems and groups of interacting subsystems is done when needed. (5) The control system is revised based on these findings. (6) Hardware selection is adjusted. (7) Final system performance is verified. (8) Hardware selection is finalized. (9) As much test verification as is practical is done.

Since the CELSS is large and complex, one should not expect the system configuration and the control system configuration to materialize without iteration. The system development process must be structured so that all its aspects can grow as system requirements come into focus, new methods become available, new technology becomes available, and as personnel are brought into the program. The effectiveness and the efficiency of the program depends on accomplishing this structuring goal.

There is adversity to achieving required system performance in each of the phases, and it is the dealing with these adversities that is the subject of this discussion.

Performance Robustness: The Ultimate Goal

Formally, it is sufficient to say that the goal of the systems control/systems management problem is "performance robustness" after making suitable definitions. This is a word parsimonious action, but it is not transparent to the many details and issues to be addressed. However, it is well worthwhile to formalize the terminology.

A complete performance specification will define and describe the required system performance in a complete and rational way. It will also define and describe the adversities which the system must overcome in the process of providing the specified performance.

[1] Mailing address

Definition: PERFORMANCE ROBUSTNESS. (1) If a system is freed so that it initially satisfies the performance specifications, and if it will continue to satisfy the performance criterion for all subsequent time for all possible results of the adverse influences declared in the performance specification, then the system is said to be performance robust to the adversities with respect to the performance criterion. (2) If a system is freed so that it initially does not satisfy the performance specifications but comes to satisfy the performance specifications in a finite period of time for all possible results of the adversities, and subsequently satisfies the performance specifications for all subsequent time for all possible results of the adverse influences declared in the performance specification, then the system is said to be performance robust to the adversities with respect to the performance specifications.

A ***robust control*** is a control system which causes a controlled system to provide performance robustness.

Adversities to Performance Robustness

It is in confronting the details of the nature of the adversities that the robust control problem comes into focus and that the means of dealing with this level of complexity can be brought into focus. Historically, performance robustness has always been the goal of the control synthesis/design activity. However, until relatively recently the concept was not sharply defined and means of its pursuit were not known or available. These means are: low-cost high volume, high speed computation, mathematical modeling, mathematical and numerical analysis, and the capability of simulation of large-scale dynamic systems. All of these are necessary for the general task of control system development. A characterization of these uncertainties follows.

System rate model functional form error. It should be expected that the functional forms of the rate models will not exactly predict the actual system rates. A most common example of this reality is the result of the use of linear rate forms (with which we are best equipped to deal) to approximate nonlinear rates. This is the case in which we know more accurate representations, but we wish to take advantage of the use of a more convenient form. A very different source of such uncertainty is the modeling of the dynamic processes of such subsystems as vegetation, which is not currently well-known. In this case, the best known functional forms do not exactly describe the dynamics of the vegetation.

System rate model parameter uncertainty. It is generally true that we cannot know the parameters of the model of a system exactly (even if we knew the functional forms exactly). As an example, in mechanical systems, the linertias cannot be known exactly although Newton's laws, in terms of functional form, are well established.

Unknown and ignored dynamics. For the most part, the effects of dynamics of the actual system which are not represented in the model are among the most difficult to quantify, and least is known about dealing with this source of uncertainty. Ignored dynamics falls into two categories: that which is specifically unknown and that which is known but is ignored in order to reduce the mathematical complexity of the model.

It can be said that dynamics which contribute to "unstable" system behavior cannot validly be ignored, and that, as is typical, most is known about dealing with ignored stable dynamics of nominally linear systems /1/, /2/.

System additive disturbance. "Additive disturbances" is the category of uncertainty which characterizes that impact of the environment of the system on the system in such a way as to add to the effect of the system's inherent dynamics. Examples of such disturbances are: change in commanded system conditions time history ("management," or "tracking" commands) and unscheduled crew activity.

Tracking commands. "Tracking commands" are signals issued to the control system which characterize the desired time history of the variables of interest of the overall system ("controlled outputs"). Tracking commands are certainly not "unknowns" or "uncertainties" in the conventional sense. However, it is easily demonstrated that tracking commands impose performance robustness factors on the system which are entirely equivalent to combinations of additional dynamics and additive disturbances.

Actuator subsystem effort uncertainty. Actuators, the subsystems which convert the power necessary to impose control commands on the system, generally are subject to both additive disturbances and the uncertainty due to unmodelled dynamics.

Measurement subsystem uncertainty. The measurement subsystem, which is composed of the sensors and the signal conditioning equipment which generates the data processing signals from the sensor variables, is generally subject to both additive disturbance and the uncertainty due to unmodelled dynamics.

Component failure. Component failure is the most visible source of potentially catastrophic system performance failure. Either control subsystem components or measurement subsystem components could be involved in this occurrence, although actuator subsystem components are more likely to fail due to moving parts and power modulation.

Software faults. Since the CELSS is large-scale and complex, the overall management and control software is expected to contain many instructions with complex logic and computation. It is projected that in the next generation of high performance aircraft, the control system software will contain in the order of two million instructions /3/. Such being the case, one or more faults in the sequence of instructions should be expected.

ISSUES

Having recognized the phases of the general control system generation process, having defined performance robustness, and having listed the categories of adversities to achieving performance robustness, we can now examine the issues which relate to performance robustness.

To analyze the issues which confront the development of the CELSS management/control system, it is useful to divide them into three groups: (1) the control system development process, which deals with adversities to obtaining required performance and control system synthesis, (2) the integration of newly available capabilities into the system development process, and (3) miscellaneous points which are raised from different perspectives, whether they are in fact contained in the first two.

The Control System Development Process

Mathematical modeling. In principle, mathematical modeling provides the means of including individual physics in the process of prediction of dynamic system behavior without requiring the operation of the actual system itself. This is done via the synthesis of (time) differential or discrete-time (multistage) equations which account for the action of the important physical processes in action within the system, the impact of external effects on the system, and the manner in which they all interact. The practical reality, however, is that no mathematical model can exactly describe the behavior of a physical system of the complexity which CELSS implies, and therefore it must be expected that the model will make predictions which are at variance with the true outcome. That error must be dealt with in a quantitative way.

The suitability of the mathematical model for control design is determined by the physical properties of the system and the control objective. The modeler must decide whether the system is best represented in the continuous or discrete time domain, whether distributed phenomena can be suitably represented by lumped models (i.e. the need for partial differential equations versus the adequacy of ordinary differential equations), and whether the nonlinear phenomena in the system must be fully accounted for. Robustness considerations are involved in the selection of the time scale of the model. Fast stable dynamics, which are usually ignored in conventional control analysis, cannot necessarily be neglected in the design of robust controllers. Robustness considerations also arise in selection of the level of aggregation in modeling, particularly with respect to biological phenomena.

The role of mathematics and mathematical modeling in control theory is elegantly developed in /4/. Some particularly relevant passages from that document are excerpted in the following. Some are direct quotes and some are paraphrased.

The mathematical modeling issue in control design differs from that in scientific research. The fundamental challenge in control modeling is to find parsimonious representations of complex physical and biophysical phenomena which are adequate for the analytical and computational needs of control design. For scientific understanding, great emphasis is placed on developing microscopically accurate models derived from physical laws. In theory, once such a model is firmly established, the control design based upon it is at least computationally feasible but may be so complex as to be impossible to implement. It may not be possible, however, to write down exact dynamic laws since processes, such as some biophysical responses to the special environments produced in a CELSS, may be poorly understood.

It is well established that feedback reduces the effect of uncertainties including modeling errors. This would imply that, in the extreme, model imperfections are not relevant in the context of control. From such a perspective, what would be needed is a powerful feedback design methodology yielding a robust, fault-tolerant control system. The process of control modeling therefore involves identifying the appropriate mathematical structure - rich enough for adequate problem description yet simple enough for mathematical tractability - and then bringing the power of mathematical machinery to bear on the solution of the control problem.

(1) Mathematical model for control system synthesis. It is characteristic of the system control problem to employ simplified models for the purpose of controller synthesis. These models typically (a) employ functionally more simple representations of process behavior and (b) do not describe all stable dynamics. It is a practical fact that much insight and intuition is necessary to obtain such a model that is sufficiently comprehensive with minimum complexity. Examples of mathematical models related to or developed for CELSS systems control applications appear in /5/ - /11/.

(2) Simulation for performance demonstration. A computer implementation of the performance demonstration model would fall in the category of "simulation model" in the terminology of many. Simulation models are valuable tools for demonstrating and testing the performance of systems. Scenario studies can be conducted to verify the effectiveness of the control design. Computer simulations, based on more comprehensive and more nearly complete models than those used for control system synthesis and include at least the most significant nonlinearities, can be utilized to demonstrate controlled system performance. Example of models developed for use in simulation of CELSS systems appear in /5/, /9/ - /18/.

Important properties of simulation models are portability and modularity. Portability of a model to various computers with little modification enhances communication among researchers and makes models more readily adapted to state-of-the-art developments in computer hardware. Modular design of modeling software allows system design option variations to be examined easily without significantly affecting the programming code of the remainder of the model.

Many simulation techniques are currently being developed which allow data entry through graphical techniques for general purpose simulations /19/, for generalized environmental control and life support system design and analysis /20/, and for control system design /21/ - /23/. Graphical interfaces greatly ease the data input process and reduce the problems associated with programming errors. The utilization of a graphical input simulation technique which accommodates the biophysical and physical processes involved in the CELSS system would be valuable in controlled system validation.

(3) Limitations on linearization. It is common practice in control system synthesis to produce linearized approximations of the system representation which are suited for this purpose. There are myriad examples of the spectacular success of this approach. In the case of large scale complex systems, of which CELSS is an example, there are limitations to the applicability of linearization, and this has been formalized /24/.

Control system synthesis and robustness analysis. Any stabilizing control system *might* be robust. The truly outstanding result of the robust control perspective is the means of proving robustness. However, the emerging leading methods of robustness analysis incorporate in their structure the means of robust control system synthesis. Thus it is most efficacious to discuss synthesis and robustness analysis together. Progress has been made in two broad categories of perspective: (1) synthesis and analysis in the time domain and (2) analysis in the domain of the Laplace transform independent variable.

(1) Synthesis and analysis in the time domain. Three overtly different forms of time domain robust control system structure generation are actively developing. In robustness considerations some well-defined form of stability plays a leading role, and all three methods are based on the Direct Principle of Lyapunov which requires expression of the equations of dynamics in the state variable form and, in some cases, in a contraction space /25/.

Adaptive control. A truly compelling concept in robust control synthesis, adaptive control has been the subject of intensive research and development activity since its coming to the attention of the (Western) control community in the late 1950's. It has had spectacular success in some highly specialized and environmentally isolated applications, but has not yet been developed to the stage of a generally applicable control strategy. Global practical stability has proven to be elusive for the broad spectrum of uncertainties.

Binary Control systems. Developed by Emelyanov and coworkers /26/, Binary Control structures are very flexible and can include on-off controls as well as continuous controls with robustness proofs possible for many combinations of adversities. The most well-known subset of Binary Control structures is Variable Structure with Sliding Modes, promoted in the West by Utkin /27/ and others.

Control synthesis via the Direct Principle of Lyapunov. A rather wide spectrum of control forms can be structured in ways suggested by use of the Direct Principle of Lyapunov. Leitmann /1/ and others have explored a special form of robustness enhancement, and others (Hollot, /28/, Schmitendorf, /29/, Blackwell, /25/) have coupled the Algebraic Riccati Equation with the Direct Principle of Lyapunov to synthesise robust control systems for nominally linear models of systems to be controlled.

(2) Synthesis and analysis in the Laplace domain. Control system development in the Laplace domain, pioneered by Bode and Nyquist in the West, has been historically the primary approach for single output variable, single control variable controller synthesis (the typical servomechanism situation). It has been extended to multiple control input - multiple controlled output form and combined with a robustness analysis procedure in H_∞ to provide an attractive procedure. An additional attraction to those already familiar with and attached to the historical form is that it offers a less intimidating prospect than that of becoming comfortable with the unfamiliar state variable/time domain methods. We will formally acknowledge four versions of this category of robust control analysis/synthesis perspectives.

H_∞ optimal control. Developed by Zames and others /30/, this approach searches for controllers which stabilize an entire set of systems to be controlled /31/.

μ synthesis. Developed by Doyle /32/ and others, μ synthesis incorporates means of accounting for "structured uncertainty" in H_∞.

Quantitative Feedback Theory. Developed by I. Horowitz /33/, this perspective is based on the view that a *set* of systems represents the system to be controlled with every possible combination of the uncertainties, each member of the set being the system to be controlled with one combination of the uncertainties. The object is to find a control system which will cause all systems in the set to perform acceptably. If such a control system can be found, it is a robust control by definition. Some of the important details of the theory have been controversial.

Linear Quadratic Gaussian with Loop Transfer Recovery. Developed by Athans /34/ and others, this perspective represents the conversion of part of a classical result in state variable/time domain theory to the Laplace domain. It has been found to be difficult to apply to certain types of practically significant systems.

> *Comment: All of the methods described above are the subject of continuing research and development. Each has attractive features and each has weakness. As each has been developed more completely, the results they produce for compatible systems become more nearly the same, with some relying partially on analysis in the other to produce results more effectively, e.g. H_∞ analysis uses state variable results for certain required parameterizations.*

The authors remain generally open-minded about the merits of the candidates, but view the Direct Principle of Lyapunov as having the greatest potential for direct application to robust nonlinear systems development, and thus having greater likelihood of applicability to some CELSS problems. Illustrations of the application the Direct Principle of Lyapunov to CELSS related systems appear in /35/ and /36/.

Integration of Newly Available Capabilities

A number of capabilities have become available which have impacted the systems control discipline or have significant potential to impact it.

(1) Object oriented programming structures. Object oriented programming structures offer a new level of clean, crisp, programs for simulation and control algorithm applications. This structure is highly compatible with multiple programmer program generation and integration /9/. It should be integrated into the CELSS program activities at every level.

(2) Artificial intelligence/expert systems. The artificial intelligence/expert systems structures show much promise for applications in the implementation of the logistics of systems management (issuing of tracking commands and execution of other automation tasks /37/, /38/). There is some evidence that in some quarters, artificial intelligence is thought of as having great general potential as a means of robust control. There are compelling arguments to the contrary, and no convincing results have as yet been produced.

(3) Neural networks. Rapid computation of nonlinear functions is assured to be of value in the CELSS program, since the CELSS contains many nonlinear process, and some control laws are likely to be nonlinear. Neural networks promise this rapid, accurate calculation capability, and should be included into the CELSS program plan /39/.

(4) Parallel processing. Parallel processing provides an economical means of increasing instruction execution rates, and is sure to be valuable in the CELSS. Both dedicated parallel processors and such configurations as Hypercube (being developed, among other places, at the Jet Propulsion Laboratory) promise to be useful.

(5) Formal methods of software design and documentation. Software design and documentation is well on the way to being a

mature engineering field, one which has grown along with structured and object oriented programming. In a previous example, we cited the prospective two million instructions of a new generation high performance aircraft; it is not out of the realm of expectation that the overall CELSS management-automation-control control software will be sufficiently large to make it crucial to have such consistently structured high level instruction sets and commensurate high quality documentation of that software.

Miscellaneous Issues

(1) Chaotic behavior. The possibility of "chaotic behavior" of the CELSS has been raised as a threat to system integrity /40/. Chaotic behavior of controlled systems is not a newly observed phenomenon. The "hunting" behavior observed for the first time in the 1940's to occur as the result of integral control action in the presence of coulomb friction is an example of chaotic motion. It should be kept in mind that chaotic dynamics is characterized by bounded variations of the variables involved, and this implies robustness with respect to some rational criterion. The conclusion to draw is that one should be alert to the possibility of excessive chaotic behavior, but of itself, chaotic behavior constitutes no more threat to robustness than do the disturbances, for example.

(2) Hardware evaluation and development. It should be expected that due to the especially rigorous and exotic requirements on the CELSS, an extraordinarily well staffed and equipped component and subsystems hardware test and development laboratory should be formed.

(3) Slowly responding sensors and actuators. It is well established that in some cases, sensors and/or actuators exhibit inherent dynamics which are "slow" compared to the dynamic behavior needed for robust performance. In some cases, at least, precise knowledge of the dynamics can support "input identification" which increases the speed with which the value of an input can be estimated. Examples related to CELSS are membrane-based separation processes and fluid concentration analyzers.

(4) Strategy for dealing with the magnitude and complexity of the CELSS systems control development problem. In the case of systems having the size and complexity of CELSS, it is important that the scale of the activities must be planned and coordinated so that it can grow with the development of the system. As examples, both the control system development model and the performance demonstration model should be structured (as an example, use object oriented programming) to support orderly, well organized growth as more and more effects are included in the control system development.

(5) Fault tolerance. Providing performance robustness in the presence of component failure is important, and is approached from a perspective different from the other sources of adversity. To have redundancy is the only means of overcoming performance loss due to failure, but it has become recognized that in the context of systems control, redundancy can take on more than one form.

Initial efforts to deal with failure were simply to have multiple copies (typically three) of exactly the same item. This is not always physically possible, and when it is, there arises the problem of detecting failure and deciding which item failed. It has been more recently realised (from fundamental linear systems control theory) that redundancy in control actuator effects and sensor information can occur without exact multiple components. Thus additional kinds of sensing and actuation can provide redundancy and fault tolerance without exact multiple components /3/.

(6) Unique aspects of the CELSS. In the effort to put the CELSS control system development in perspective, it is constructive to compare with other complex systems NASA has developed. There are many similarities and prospectively, many similar problems and common utilizations of control actions and methods. However, the CELSS will include crop plants which are a vital part of system operation, and CELSS must perform robustly for unprecedented periods of time.

It is generally acknowledged that the dynamics of growth and gas exchange of plants in closed controlled environments are currently not well understood, and thus the mathematical models of these processes will reflect greater uncertainty than those of the more conventional technical systems. Thus this aspect is unique to CELSS.

The requirement for robust performance for unprecedented periods of time puts added weight on the development of fault tolerance. The degree of fault tolerance needed for CELSS is also unique.

CLOSING COMMENTS

We have discussed the issues of dynamic systems control as they relate to CELSS, a system which must perform robustly to support humans in the space environment. Means are now available to carry the pursuit of robust performance for systems having adversities which are characteristic of CELSS significantly further than ever before. All the methods which were discussed are in continuing development, and thus ever increasing capabilities can be expected to become available for addressing the robustness requirements for CELSS. No single method is available to resolve the entire robust performance problem in a non-iterative way. Consequently, one should expect to use the compatible strengths of all available methods in conjunction with newly emerging techniques in software engineering and design.

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